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RESEARCH LABORATORY

FINAL TECHNICAL REPORT

RESEARCH ON NON-EQUILIBRIUM
PLASMA PHYSICS

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ABSTRACT

An experimental study of shock waves produced in a T-tube and a theoretical study of electron-ion reaction rates are summarized. Precursor ionization in the T-tube was observed, but no conclusive evidence concerning the source of the ionization was obtained. The study of electron-ion reaction rates resulted in a detailed theory for the rate of three body electron-ion recombination and radiative decay in monatomic gases. Comparison of this theory with published measurements in helium, argon, mercury, and cesium shows very good agreement.

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SECTION 1

INTRODUCTION

The experimental and theoretical research performed under this contract was directed toward understanding two phenomena. In the early phase of the program an experimental study using a T-tube was directed toward producing and investigating collisionless magnetohydrodynamic shock waves. This was supplemented by an in-house theoretical study of the generalized equations of plasma physics. It was found in the experimental phase that a collisionless shock could not be produced in a T-tube. Recently, based on a suggestion that grew out of recent theoretical work under this contract, Petschek¹ and Gerry² have shown that Patrick's experiments³ may be interpreted using a collisional model more satisfactorily than using the collisionless model proposed earlier.⁴ Thus up to now there is no evidence that a collisionless magnetohydrodynamic shock wave has been produced in any laboratory experiment. This now appears to be a much more difficult task than was anticipated several years ago.

In the later phase of this program a theoretical study of the electron-ion ionization and recombination rates and the radiation from partially ionized gases was carried out. The electron-ion recombination theory, published in Refs. 5 and 6, is in good agreement

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with published experimental data. An additional publication on the quasi-steady ionized state is now in preparation.⁷ This theory has been applied to the determination of non-equilibrium gas properties in a nozzle expansion and in a crossed field accelerator, to be presented at the March, 1963, ARS Electric Propulsion meeting.⁸ The theory has also been applied to the study of non-equilibrium ionization in crossed field magnetohydrodynamic generators, to be included in a paper submitted to the April, 1963, meeting on Engineering Aspects of Magnetohydrodynamics.⁹ These three papers acknowledge support of AFOSR under Contract AF 49(638)-670 as do those published previously.^{5,6}

A more detailed discussion of the T-tube study is given in the Technical Summary below. The work on non-equilibrium plasma properties can be found in the technical papers quoted above. The abstracts of these papers are given in the Technical Summary below.

SECTION 2

TECHNICAL SUMMARY

2.1 T-TUBE STUDIES

A 6 inch inside diameter T-tube,¹⁰ 2 meters long was constructed. Driven by 2 one microfarad 125,000 volt capacitors, generally operated at 50,000 volts, shock waves of Mach number 10 to 70 in helium, nitrogen, and air at an initial pressure ranging between 1 and 100 microns mercury were produced. A pair of Helmholtz coils, 1 meter in diameter, separated by 8 inches, and driven by a 100 kw motor generator set was used to establish a magnetic field of 800 gauss through the T-tube transverse to the direction of shock propagation. A radio frequency transmitter and associated circuitry were developed to pre-ionize the gas, but had no influence on any of the experiments because the ionization produced in this way was considerably less than the pre-ionization produced by the discharge itself. Details on this experimental setup can be found in Ref. 10.

The velocity of the luminous front produced in the test gas by the T-tube discharge was measured using photomultipliers as light detectors. This luminous front is considered to be the shock front. In order to arrive at a time history of the shock velocity a series of shots was made with two detectors at various positions down the tube. Considerable

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difficulty was encountered because of irreproducibility and because of electrical noise occurring in the initial 10 microseconds of the discharge. However, reliable data were obtained which showed that the shock velocity decays inversely with the square root of the distance travelled. This is a more rapid decay than that expected on the basis of one-dimensional blast wave theory¹¹ and is also more rapid than that observed in another experiment.¹² It is believed that this excessive decay rate is due to additional energy loss mechanisms, as yet undetermined.

Measurements of shock velocities in different gases were also made with the externally applied transverse magnetic field. In helium the transverse magnetic field caused the shock velocity to decay more rapidly than without the field as would be expected qualitatively. In nitrogen and air the magnetic field had very little influence on the shock speed. The presence of a radio frequency glow discharge in the T-tube prior to initiation of the shock had no measurable effect on the shock velocity, either with or without the applied transverse magnetic field.

Magnetic loop measurements were made with and without the magnetic field in air, nitrogen, and helium at 25 microns. These signals indicate that electrical currents were induced behind the shock front when the magnetic field was applied. Maximum loop response was obtained when the plane of the loop was perpendicular to the transverse magnetic field. There was considerable variation in structure and polarity in the loop signals in all gases. No correlation to gas parameters could be made. For air and nitrogen, onset of the loop signal occurred near the maximum of the signal from the photomultiplier recording emission from the gas near the magnetic loop. There was no evidence that a magnetohydrodynamic "collisionless" shock wave

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had been produced nor was it possible to interpret the loop signals either on the basis of mhd shock wave theory¹³ or on the basis of a qualitative description of T-tube performance.

From these measurements it is concluded that there is little hope of producing "collisionless" shock waves in the T-tube. It is possible to produce the type of magnetohydrodynamic shock wave described by Marshall¹³ but no meaningful analysis of this type of wave can be made because the path of return currents is not known and is very difficult to measure or to compute.

Additional experiments were made in order to gain information on the state of the gas in the T-tube, both ahead of and behind the shock wave. In prior studies of shock wave phenomena, an apparent precursor ionization appearing prior to the arrival of the shock front has been reported,¹⁴⁻¹⁶ although the source of this remains uncertain. An attempt was made to verify the existence of precursor ionization in this T-tube and to determine some of the gas properties under this condition. Photomultiplier measurements of gas luminosity, 9 kmc microwave transmission, and magnetic loops were used. After sufficient precautions were taken, the electronic noise on the photomultipliers was reduced below the signal level during the full duration of the discharge. The first 20 microseconds of the microwave transmission signals were obscured by noise.

Without going into detail, the following conclusions can be drawn from these experiments. An initial electron density is produced in the T-tube at the time of firing the driving discharge, prior to arrival of the shock wave, when using helium, nitrogen, or air at initial pressures between 1 and 100 microns mercury. This is substantiated by photomultiplier measurements and by microwave measurements. From the microwave measurements, the electron density is found to exceed 10^{12} cm⁻³, corresponding to a degree of ionization as high as 1%. From the

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photomultiplier measurements, using the magnetic loop as the timing standard, no evidence of a slow wave propagation mechanism for the production of this ionization is seen. The initiation of precursor luminosity is so rapid that the signal speed must be in excess of 2×10^8 cm/sec. From this, it is postulated that the cause of this ionization is either absorption of ultraviolet radiation emitted in the discharge region or electrical breakdown throughout the length of the T-tube. To ascertain the importance of the electrical breakdown effect, magnetic loop measurements were made. No direct evidence of breakdown currents could be found. This does not eliminate breakdown as a possibility, but does not offer any evidence in support of it. It was found that a ground connection through the vacuum system at the far end of the T-tube contributed to the current observed along the length of the tube, prior to shock arrival. Elimination of this ground altered the loop measurements but did not appreciably alter the photomultiplier and microwave observations of precursor luminosity and ionization.

All of the precursor observations described above are qualitative and without adequate controls to insure completely their validity. A more complete study with very rigid controls is required to uncover completely the mysteries of T-tube operation.

2.2 NON-EQUILIBRIUM PLASMA PROPERTIES - ABSTRACTS OF PAPERS

2.2.1 S. Byron, R. C. Stabler, and P. I. Bortz, Phys. Rev. Letters 8, 376 (1962), "Electron-Ion Recombination by Collisional and Radiative Processes"

Considerable progress has been made recently in electron-ion recombination theory by calculating the contribution to the recombination rate due to (1) three-body capture into excited states,

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(2) collisional de-excitation, and (3) radiative de-excitation. In this note we point out two physical principles that dominate this three-body recombination process and form the basis of a simple general method of calculating both the electron temperature and the net rate of three-body recombination.

First, under equilibrium conditions there exists a pronounced minimum in the total rate of de-excitation of atoms as a function of the principal quantum number, n , of the excited state. This minimum serves to limit the net rate of three-body recombination to the rate of de-excitation of the level, n^* , at which the minimum occurs. Second, that part of the energy of recombination given to the electrons in three-body capture and de-excitation collisions must be transferred from the electrons to the ions and atoms through elastic collisions. Because the net rate of three-body recombination is very sensitive to the electron temperature, the electron energy equation plays a dominant role in collisional recombination calculations.

2.2.2 S. Byron, R. C. Stabler, and P. Bortz, Bull. Am. Phys. Soc. 11, 328 (1962), "Electron-Ion Recombination in Discharge Afterglows*"

The rate-limiting factors in the collisional recombination of electrons and ions in discharge afterglows are (1) the rate of de-excitation by collisions and radiation of the state for which the total equilibrium de-excitation rate has a minimum, and (2) the rate of elastic energy transfer between electrons and ions. The nonequilibrium electron temperature and the recombination rate are obtained from simultaneous solution of the equations for the minimum de-excitation rate and the electron energy balance. The three-body character of the collisional recombination and de-excitation process is masked by the time rate of change of

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the electron temperature. The net rate of recombination exhibits a two-body density dependence ($dN_e/dt = \alpha N_e^2$, where α is independent of N_e) because of the two-body behavior of the elastic-energy transfer rate. Early results of the application of this theory to recombination in discharge afterglows are given in the following:

Gas	$T_e(\text{exp})^1$	N_e	$\alpha(\text{th})$	$\alpha(\text{exp})^1$
Argon	3100	3×10^{12}	2×10^{-10}	2×10^{-10}
Cesium	2000	5×10^{12}	4×10^{-10}	3.4×10^{-10}
Mercury	2000	10^{12}	3×10^{-10}	2.3×10^{-10}

¹S. C. Brown, Basic Data of Plasma Physics (MIT Press, Cambridge, Massachusetts, and John Wiley & Sons, Inc., New York, 1959), p. 195.

2.2.3 G. R. Russell*, S. Byron, and P. I. Bortz, submitted to the March, 1963, ARS Electrical Propulsion Meeting at Colorado Springs, Colorado, "Performance and Analysis of a Non-Equilibrium Crossed Field Accelerator"***

A theoretical and experimental study has been made of a steady supersonic free jet crossed field accelerator, using monatomic gases. The experimental studies were made utilizing a 40 kilowatt thermal arc to heat argon or helium at mass flow rates ranging between 0.3 and 2.0 grams/sec. Acceleration was produced by adding up to 70 kilowatts of electrical power for a duration of up to one hour to the supersonic flow in the presence of a transverse magnetic field ranging between 700 and 2500 gauss. Calorimetric measurements, direct free stream velocity

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profile measurements, and static and total pressure measurements were made. The free stream velocity was increased by more than a factor of three at accelerator exit Mach numbers of about 2. The thermal efficiency of the accelerator, measured by calorimetry, ranges between 60 and 70 per cent and is in agreement with efficiencies computed on the basis of pressure and velocity probe measurements.

The free stream velocity is determined by recording the voltage between two probes inserted in the supersonic stream in the region of a weak applied transverse magnetic field. The output voltage of the probe is linearly dependent on magnetic field strength, independent of probe current (for small currents) and independent of Debye sheath voltages.

A one-dimensional theory of constant pressure supersonic crossed field acceleration is presented for the two limiting cases of frozen and equilibrium electron densities. The theory shows that, for large increases in the plasma velocity and for degrees of ionization less than about 5 per cent, the accelerator exit Mach number approaches $(3)^{\frac{1}{2}}$ irrespective of the accelerator initial Mach number. At this asymptotic Mach number the kinetic energy and thermal energy of the stream are equal.

A theoretical analysis of the state of the ionized gas in the supersonic nozzle and accelerator section has been carried out using a two-fluid plasma model, treating the electrons and the ions and atoms as a mixture of two perfect gases having unequal temperatures. The starting points for the theory are the applicable radiative transition probabilities and the cross sections for collisional ionization, recombination, and de-excitation (found in Reference 1). The supersonic nozzle expansion has been programmed and solved on an IBM 709 for the two limiting cases of an optically thin and an optically thick plasma. The gas at the exit

¹S. Byron, R. C. Stabler, and P. I. Bortz, Phys. Rev. Letters 8, 376 (1962).

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of the nozzle (at a Mach number of 3) remains about 1 per cent ionized at an electron temperature about 1000°K higher than the atom temperature.

A similar 709 computer program has been run for an optically opaque argon plasma with an applied electric and magnetic field using the rates of Reference 2. The results show a very rapid rise in electron temperature (in excess of 10^4K) dependent on the applied electromagnetic field, followed by a rapid rise in the degree of ionization from 1 per cent to as much as 8 per cent for current densities of the order of 100 amp/cm^2 . It is found that the electrical conductivity of the gas is dominated by reaction rate processes and changes by more than an order of magnitude as the gas passes through the acceleration region.

²H. Petschek and S. Byron, Annals of Physics **1**, 270 (1957).

2.2.4 S. Byron, P. I. Bortz, and G. R. Russell, submitted to the April, 1963, Meeting on Engineering Aspects of Magnetohydrodynamics at Berkeley, "Electron-Ion Reaction Rate Theory: Determination of the Properties of Non-Equilibrium Monatomic Plasmas in MHD Generators and Accelerators and in Shock Tubes"*

The theoretical analysis required to determine the electron density, electron temperature, excited state populations, and radiation emission in monatomic plasmas is presented. Calculations of collision cross-sections using the semi-classical method of Gryzinski¹ for some of the noble gases and alkali metal vapors are given. Available information on radiative transition probabilities is reviewed. Because self-absorption is significant over the density and temperature range found in MHD

*Supported in part by the Air Force Office of Scientific Research under Contract AF 49(638)-670.

¹M. Gryzinski, Phys. Rev. **115**, 374 (1959).

devices and in shock tube experiments methods for calculating plasma properties are given which include self-absorption.

In general a three-fluid, three temperature model of the gas is required, but quite often a two fluid model will suffice. The dominating features are the reaction rate equations and the individual energy equations for each specie. Under quasi-steady conditions it is found from the kinetic equations that a critical excitation level, N_c , of the neutral atom is found for which $\sigma_{c,c-1} \bar{v}_e N_e = \sum_{i < c} A_{c,i} (1 - f_i)$, where $\sigma_{c,c-1}$ is the cross-section for de-excitation of level c to level $c - 1$ by electron impact, \bar{v}_e is the mean electron speed, N_e the number of electrons, $A_{c,i}$ the radiative transition probability from level c to a lower level i , and f_i is the fraction of emitted photons of frequency $h\nu_{c,i}$ that are self-absorbed in the plasma. Above the level N_c the population of excited states is equilibrated with the free electron density through inelastic collisions with electrons and can be computed from statistical mechanics, using the "lowered" ionization potential^{2,3} and the electron temperature. The population of the levels N_c and below (including the ground state) relative to the number of free electrons is computed from the rate equations for these states, which include electron excitation and de-excitation collisions and radiative emission and self-absorption. The position of the critical level is unchanged when there is rapid ionization or electron-ion recombination, except in the case of electron-ion recombination at low electron temperatures. The electron temperature is determined by combining the electron energy equation with the reaction rate equations.

²G. Ecker and W. Weizel, Ann. Phys. 17, 126 (1956) and Z. Naturf. 129, 859 (1957).

³H. N. Olsen, Phys. Rev. 124, 1703 (1961).

Applications of this reaction rate theory fall into the 3 categories, (1) electron-ion recombination rate, (2) ionization rate, and (3) quasi-steady state. The first category has been treated in Ref. 4 for optically thin hydrogen-like atoms and shows good agreement with experiment when applied to helium, argon, mercury, and cesium. All three categories have been treated in Ref. 5 for optically thin atomic hydrogen and alkali metal vapors and in Ref. 6 for optically thick atomic hydrogen. Three additional applications of the theory are given here.

Quasi-steady values for the unknowns T_e , N_e , N_i , and $I(V)$, where $I(V)$ is the radiation intensity from a 3 cm diameter cylindrical plasma, are given as a function of the atom density and temperature in shock heated xenon. Quasi-steady non-equilibrium values of the electron temperature and electron density in a segmented electrode mhd generator using helium cesium mixtures as the working fluid are given as a function of the total atom density, the atom stagnation temperature, the flow Mach number and the Hall parameter, $\omega_e \tau_e$. The electron density, temperature, and electrical conductivity in a solid electrode crossed field accelerator using helium as the working fluid are given as a function of distance along the streamline for a particular entrance condition and for several values of magnetic field strength. The magnetic field and applied voltage are assumed to have a Gaussian distribution along the flow direction.

⁴S. Byron, R. C. Stabler, and P. I. Bortz, Phys. Rev. Letters 8, 376 (1962).

⁵D. R. Bates, A. E. Kingston, and R.W.P. McWhirter, Proc. Roy. Soc. A 270, 155 (1962).

⁶D. R. Bates, A. E. Kingston, and R.W.P. McWhirter, Proc. Roy. Soc. A 267, 297 (1962).

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